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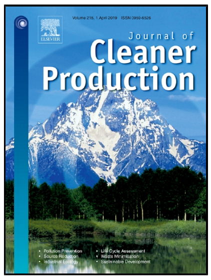

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Wind Shear Effect on Aerodynamic Performance and Energy Production of Horizontal Axis Wind Turbines with Developing Blade Element Momentum Theory

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Abstract

Nowadays, the optimal use of energy is one of the most important things in energy engineering. Disadvantages of fossil fuels make renewable and cleaner energy sources more widely used. Wind energy is a type of clean energies that will help humanity transition to a sustainable future. The power of wind turbine depends on many parameters such as wind profile and blade geometry. In most studies, wind speed is generally considered to be constant and uniform along the rotor blades. But in fact the nature of wind has irregularities in space and time. Moreover, wind shear leads to non-uniformity in wind vertical profile. Having a good understanding of these kinds of spatial and transient irregularities and also their influence on wind turbine performance reduce uncertainty in design process. In the present study the blade has been designed by blade element momentum (BEM) theory and aerodynamic coefficients have been calculated along the blade length. The effects of wind shear have been studied on the designed blade. Power law has been used to model wind shear. By merging this function with BEM theory, its effect can be calculated along the blade length. Results show that wind shear has little impact on aerodynamic coefficients near the root region. Most of changes occur at 0.2 to 0.8 of the blade length.

Furthermore, existence of shear in wind profile regarding the turbine designed for uniform inflow, reduces the kinetic energy flux, ability to extract the available potential and power generation.

Keywords: Wind Energy; Horizontal Axis Wind Turbine; Aerodynamics; BEM; Wind Shear Effect; Power Coefficient.

1. Introduction

The disadvantages caused by fossil fuels have made human to use clean energy as an alternative for years. From renewable energies, wind energy has been used widely due to its availability. In recent years, researchers spend their time and knowledge on this type of energy. Chen et al. (2018) tried to minimize the turbine cost of energy based on wind statistics. This aim was done by a mathematical approach. The result of this study led to a guideline to minimizing turbine cost of energy. One of the most influential factors on wind turbine power production is rated wind speed. Sedaghat et al. (2017) found a formulation between rated wind speed and wind turbine power curve by introducing capacity value. The most important factor affecting lifetime and reliability of wind turbine is the blade aerodynamic forces. These forces are highly dependent on environmental conditions, especially wind conditions. Wind turbines spend most of their life time in non-uniform winds (Leishman, 2002). This wind condition affects the turbine performance (Lubitz, 2014). The problem of non-uniformity of wind conditions will be highlighted for urban wind turbines. In these turbines, because of high level of disturbance, flow domain will become complicated (Pourazarm et al., 2015). In the field of wind conditions studies, there is a standard published by international electro-technical commission (IEC). In accordance with this standard in order to ensure safety, turbine performance should be studied under severe wind conditions. The two extreme winds studied in this standard are extreme operating gusts (EOG) and energy development corporation (EDC). In this context, Storey et al. (2014) investigated aerodynamic loads on turbine under EOG conditions. In this study, flow field around turbine has been simulated by large eddy simulation (LES). Kim et al. (2014) compared performance of two bladed turbine under normal and EOG condition by HAWC2 method. HAWC2 is based on blade element momentum (BEM) theory in which dynamic stall and dynamic inlet flow have been investigated.

Many research results show that wind turbine power diagram depends on a large number of meteorological and topographical parameters. Wind shear, turbulence and wind direction are the most important parameters that affect the uncertainty of the turbine power diagram. Tahani et al. (2017) investigated the effect of geometrical parameters of an optimized wind turbine blade in turbulent flow. In this study different chord and twist distribution functions and also different sections were considered in the optimization process. The base geometry and also the optimized geometry performance were analyzed using CFD at two turbulence intensities. The results indicated that by increasing the turbulence intensity, the wake turbulent kinetic energy also increases and therefore the wake recovery occurs faster. Also the results indicated that for optimized geometry the separation is delayed and therefore more power generation can be achieved. Li et al. (2018) studied the influence of wind velocity field on the performance of offshore floating wind turbine. In this research, several wind velocity fields have been investigated such as uniform wind velocity field, sheared wind velocity field (with a smooth profile) and turbulent wind velocity field (with spatial and transient irregularities). The first two wind velocity fields were time-independent and the direction of inflow was perpendicular to the rotor plane. Kaviani and Nejat (2017) estimated wind turbine noise by implementing shear wind profile. The method used in this study is Improved Delayed Detached Eddy Simulation in order to simulate the instantaneous flow field around wind turbine. Rohatgi and Barbezier (1999) investigated the effect of wind disturbances on the turbine output. They also presented a summary of atmospheric stability and vertical temperature gradients to enhance understanding of their effects. Frandsen et al. (2000) examined the disadvantages of measuring methods by replacing a new performance analysis method. The ACCUWIND project examined the effect of secondary parameters such as vertical inflow and turbulence intensity on wind turbine performance, in order to obtain reliable power diagram. Kaiser et al. (2007) studied uncertainty in turbine power by estimating the effect of turbulence intensity. In this study, effects of wind shear and turbulence were studied separately. Schmidh Paulsen et al. (2006) performed simulations for tangential stresses and different turbulence intensities. In this research, the wind speed has been studied only at the height of the hub. Maeda et al. (2006) experimentally investigated wind turbine which had a rotor with diameter of 10 m. Pressure distribution on the rotary blade was measured by pressure transducers and mean wind speed was measured by an anemometer. Then, the relations between the aerodynamic forces resulting from the distribution of the pressure and the momentum on the blade were investigated. The results indicated the fluctuations in aerodynamic forces are resulted from variation of wind speed and direction. Maeda and Kawabuchi (2007) experimentally studied wind turbine aerodynamics by considering wind shear. They measured the wind profile using an anemometer. Wagner et al. (2009) studied vertical wind profile by experimental measurements. They used the definition of equivalent wind speed in order to simulate wind shear. Honrubia et al. (2010) measured and analyzed the wind speed at nine different heights to investigate the effect of wind shear. They used power law and logarithmic law in order to analyze measured data. Sezer-Uzol and Uzol (2013) investigated the effect of uniform and shear flow on 2 bladed turbine performance by Vortex-Lattice method. This method was also used by Jeon et al. (2014) to study unsteady aerodynamics of off-shore wind turbines. In their study, effects of thickness and viscosity were considered by a correction in the unsteady vortex method. Jeong et al. (2014) investigated the effect of wake on wind turbine aeroelastic by considering shear flow. Predictions and calculations were carried out in two modes: normal wind conditions and extreme wind conditions, and by using BEM method and free vortex method. Smith et al. (2015) experimentally studied wind profiles on an off-shore wind farm. In this study, the effects of turbulence and wind shear were investigated by measuring data during 6 months. Li et al. (2016) examined the effect of fluctuations and wind shear by using experimental research for a wind turbine in a wind tunnel. Turbulence intensity was modeled by turbulence grids and wind shear by boundary layer production tool.

In the present research, a turbine is firstly modeled by BEM method. This method is widely used in the aerodynamic aspect of wind turbine design (Bakirci and Yilmaz, 2018; Tahani and Moradi (2016)). It removes insignificant amount of computational cost and time and is sufficiently precise. By designing turbine with this method, chord and twist distributions for specific power and uniform wind speed are calculated. Afterwards the aerodynamic coefficients such as lift, thrust and power coefficient are determined along the blade length i.e. in different blade radius. After designing turbine with BEM method, effect of wind shear is studied by using the definition of power law. The swept area of the rotor is divided into different slices (segments) in the vertical direction and each slice will be exposed to a specific speed which is proportional to wind shear. The novelty of this study is to take into account the effect of wind shear with BEM method which classically uses the constant wind speed profile. Therefore, the wind shear effect on aerodynamic coefficients along each part of the blade length will be considered.

2. Aerodynamics of horizontal axis wind turbine

BEM theory had been introduced by Glauert (Hansen, 2008) and it combines momentum theory and blade element theory. In this method, the blade is divided into several radial elements (usually 10-20, (Manwell et al., 2009)). It is assumed that these elements do not have an aerodynamic interaction to each other. BEM is an analytical method which needs some parameters as inputs. These parameters include power of turbine, free stream wind speed and airfoil type. It should be noted that by selecting airfoil type, design angle of attack and also design lift/drag are determined. Identifying number of blades and using Eq. 1 (Manwell et al., 2009) will lead to determining maximum power coefficient ($C_{P,\,max}$) and optimum tip speed ratio (λ).

$$C_{P,max} = \frac{16}{27}\lambda\left[\lambda + \frac{1.32 + \left(\frac{\lambda - 8}{20}\right)^2}{B^{\frac{2}{3}}}\right]^{-1} - \frac{0.57\lambda^2}{\frac{C_l}{C_d}\left(\lambda + \frac{1}{2B}\right)} \tag{1}$$

B is number of blade which in the present study is equal to 3 and C_l and C_d are lift and drag coefficients, respectively. Rotor radius is another parameter which can be calculated by Eq. 2.

$$P = \frac{1}{2} C_p \eta \rho \pi R^2 U^3 \tag{2}$$

where η is the electromechanical efficiency and is assumed to be 0.9, P is the turbine power, ρ is the air density and U is the mean wind speed.

BEM is an iterative method which is based on guessing axial and angular induction factor. By equating normal forces and torque equations from momentum theory (Eq. 3 and 4) and also blade element theory (Eq. 5 and 6), axial induction factor (a) and angular induction factor ($\acute{a}$) will be determined (Eq. 7 and 8) (Manwell et al., 2009).

$$dT = \rho U^2 4a(1-a)\pi r dr \tag{3}$$

$$dQ = 4\acute{a}(1-a)\rho U \pi r^3 \Omega dr \tag{4}$$

$$dF_n = B\frac{1}{2}\rho U_{rel}^2 (C_l \cos\varphi + C_d \sin\varphi) c dr \tag{5}$$

$$dQ = B\frac{1}{2}\rho U_{rel}^2 (C_l \sin\varphi - C_d \cos\varphi) c r dr \tag{6}$$

$$a = 1 \Big/ \left[1 + 4sin^2\varphi \Big/ \left(\acute{\sigma} C_l \cos\varphi\right)\right] \tag{7}$$

$$\acute{a} = 1 \Big/ \left[\left(4\cos\varphi \Big/ \acute{\sigma} C_l\right) - 1\right] \tag{8}$$

where Ω is the rotational speed, r is the local radius, φ is the angle of relative wind and $\acute{\sigma}$ is the solidity ($\acute{\sigma} = \frac{Bc}{2\pi r}$).

There are two modifications on BEM which make it more realistic. The first one is applied in order to take the effect of flow behavior around the tip into account. Due to pressure difference between suction side and pressure side of the blade, the air tends to flow around tip. Prandtl has introduced a correction factor called F which is calculated by Eq. 9 (Manwell et al., 2009).

$$F = (\frac{2}{\pi})\cos^{-1}\left[\exp\left(-\left\{\frac{(B/2)[1-(r/R)]}{(r/R\sin\varphi)}\right\}\right)\right] \tag{9}$$

Another modification is for turbulent wake state. At this condition, an empirical relation for axial induction factor has been developed by Glauert (Manwell et al. 2009) for $a > 0.4$ or $C_T > 0.96$. C_T is the thrust coefficient.

$$a = \left({}^{1}/_{F}\right)\left[0.143 + \sqrt{0.0203 - 0.6427(0.889 - C_T)}\right] \tag{10}$$

A comparison between classical BEM results obtained in the present study and experimental data (Lee et al., 2016) is shown in Fig. 1. Results show good agreement between two series of data somehow the maximum difference is equal to 11.6%.

3. Considering wind shear and solution method

The lowest atmospheric layer is a turbulence layer called atmospheric boundary layer. In this layer, earth friction, climatic conditions, and vertical gradients of temperature and pressure affect the air flow. The friction caused by the roughness of the earth absorbs energy from the air and creates a vertical wind velocity gradient (Mathew, 2006). Investigating the effect of wind speed vertical gradient on turbine performance is important not only in terms of aerodynamics, but also for fatigue life of rotor blades. In order to model the vertical gradient of wind velocity, one can use the power law or logarithm law. These functions are derived from experimental data collected by scientists in the field of aerodynamics and meteorology (Jha, 2017). Equation 11 expresses the power law (Tong, 2010).

$$U_h = U_H\left(\frac{h}{H}\right)^{\alpha} \tag{11}$$

H is the hub height, U_H is the wind velocity at hub height and α is the wind shear coefficient. The logarithmic law is also defined according to Eq. 12 (Tong, 2010).

$$U_h = \frac{u_*}{k} ln\left(\frac{h}{z_0}\right) \tag{12}$$

where u_* is the friction velocity, z_0 is the roughness length and k is Kármán constant and is about 0.4 according to Elkinton et al. (2006). In the present study, wind shear is modeled by power law and using wind information in a specific area.

In classical BEM theory, wind speed is considered to be constant along the rotor height and swept area but in fact, velocity magnitude changes with height. In this research, the designed turbine has 100 kW output power, free stream wind velocity is 6 m/s and the selected airfoil is RISO A1-21. Rotor diameter is 47.2 m (from Eq. 2) and hub height is 50m. Schematic view of designed turbine is illustrated in Fig. 2. In order to apply power law for predicting wind speed profile, wind shear component should be determined. In this investigation, wind data from Moalleman city (Mirhosseini et al., 2011) has been used at three different heights. This data is presented in Table 1. By applying curve fitting process on the data, wind shear coefficient (α) becomes 0.1092. In Fig. 3, difference between the input velocities in the classical mode and shear flow mode is observed.

In the classical BEM method, the rotor is considered as a disk which is divided into a number of elements along the blade length (20 radial elements in this study). As mentioned, in this method, the aerodynamic coefficients are calculated along the blade. In order to study the effect of vertical wind profile on the rotor's performance, the swept area should be discretized by sectors (Fig. 4a). With the aim of increasing accuracy, several slices (segments) in the vertical direction of the rotor area are considered. From the collisions of the rings (radial elements) and these slices, sectors are created at the rotor surface. A sector is shown in Fig. 4b. To increase the accuracy of solution and also with the aim of investigating solutions dependency to the number of slices along the rotor height, it is divided into 5, 10, and 20 slices which are shown in Figs. 4a, 5, and 6, respectively.

The velocity of slices is calculated using power law and each sector will be subjected to the velocity corresponding to its height. It is obvious that in each slice along the rotor height, wind velocity is assumed constant. The calculated velocities at different heights for all three cases (considering 5, 10 and 20 slices) are presented in Tables 2 to 4. The slice numbering is from the bottom to top in the rotor area and it does not change when the rotor moves around the axis.

Results

As mentioned above, harnessing the wind power is one of the cleanest ways to generate electrical energy without toxic pollution and global warming emissions. Moreover, wind is affordable, abundant, and inexhaustible which makes it a sustainable and large-scale alternative to fossil fuels. In this section, results of aerodynamic design of wind turbine are presented and a comparison between classical data and results from applying wind shear is made. In the first step of design, blade geometrical parameter means the distributions of chord length and twist angle will be determined. These distributions for designed turbine are presented in Fig. 7. The r/R is the relative location from the blade root, which is used to make the results clearer. The chord distribution has uptrend from the first to the second radial element and then it decreases. The value of twist angle is decreasing along blade length. By decreasing twist angle along the blade, the angle of attack at each section remains approximately constant which leads to a constant lift coefficient. In Fig. 8, the distribution of the angle of attack is shown along the blade. The angle of attack distribution is almost constant along the blade length except in the tip region. In this region, due to generated vortices, the angle of attack decreases. In general, existence of shear in wind profile reduces the angle of relative wind. The angle of attack is obtained from the difference between angle of relative wind and twist and pitch angle (Elkinton et al., 2006). As can be seen from the figure, the reduction due to wind shear is low at the first 30% of the blade length from the root and then this reduction increases in the rest of the blade length.

Distribution of lift coefficient is illustrated in Fig. 9. Lift coefficient is almost constant along the blade length except at tip region. This trend is like to angle of attack distribution. With decreasing angle of attack in sheared inflow compared to its classical value, lift coefficient will decrease. This increase is negligible in the root region, however it has slightly grown. In order to make a better comparison, results are indicated along the blade length for cases with 5, 10 and 20 slices. These results show that by increasing number of slices, results are closer to their classical values.

Figure 10 demonstrates distribution of thrust coefficient along the blade length for cases with 5, 10 and 20 slices (segments). Classical value of thrust coefficient is almost constant and is about 0.88 along blade length except at tip and root regions. This value for thrust coefficient is related to maximum power coefficient. Wind shear generally enhances thrust coefficient along the blade length. This increase is negligible at tip and root regions but the difference between these two data series is higher for the other radial positions along the blade, particularly for case with 5 slices. Finally, in Fig. 11 effect of wind shear on local power coefficient is illustrated along the blade for cases with 5, 10 and 20 slices. In classical design, rate of increasing local power coefficient is linear from the root to 80% of the blade length. Then, it reaches its maximum value and after that it decreases due to tip vortices (Sedaghat and Mirhosseini, 2012; Sedaghat et al., 2014; Tahani et al., 2017). By rotating blades in a sheared inflow, the blades pass through the variable wind speed profile. The magnitude of the variations depends on the shear coefficient and the blade radius. The relative velocity that blades will face, determines aerodynamic forces on the blade. It should be noted that all sectors in the swept area rotate (and should rotate) with a constant rotational speed, because they are assumed to be connected to each other, however by considering the non-uniform wind profile, the wind velocity is different for each slice based on its height, so the power generation and aerodynamic coefficient of each sector is different from the other sector placed in the other slice with the same radial distance from the blade root. Therefore, all results represented in Figs. 8-11, for sheared inflow, are obtained by summation of aerodynamic coefficients of all sectors which are in the same radial bound. As observed, these results are shown versus r/R.

As the blade moves upwards, free stream velocity and hence relative velocity and angle of attack will be increased, while by moving downward everything will be reversed. These cyclic changes in the inlet flow reduce the turbine's ability to extract power from the wind. As can be seen from the figure at root region, wind shear has no significant effect on power coefficient. Most changes occur in the 70-80 % of the blade length from the root which shows at most 4.4 % reduction in local power for the case with 20 slices.

Conclusion

The presence of pollutant resulting from the excessive use of fossil fuels and phenomena such as global warming has led human to the use of renewable and clean energies such as wind energy. One of the most important aspects of wind turbine design is its aerodynamics. More accurate design based on real operating conditions causes to increase reliability for power generation and techno-economical assessment. In most aerodynamic designs of wind turbines, wind speed is assumed constant on the swept area and along the rotor height and wind shear is ignored. The aim of this study was to investigate wind shear effect on aerodynamic design of horizontal axis wind turbine. The approach implemented here was based on BEM theory. Hence, first of all, a turbine was aerodynamically designed by this classic theory. Therefore, the blade shape i.e. chord and twist distribution was determined at different blade radius and aerodynamic coefficients were calculated along the blade length. The effect of wind shear was studied on aerodynamic performance by dividing the rotor height into different slice numbers. In order to calculate velocity at each height, power law was used. So, the BEM theory was combined with wind shear effect. Results showed that wind shear has no significant effect on aerodynamic coefficient in root region. Most of changes occurred at 20 % to 80 % of the blade length. Existence of shear in wind profile led to reduction in angle of attack and hence lift coefficient. Thereby, wind turbine power coefficient reduced; however, the thrust coefficient depicted an increment. This study has implemented an innovative method to combine the BEM theory and wind shear effect that causes to increase the accuracy of classical BEM method while it has almost the same calculation cost. As a future work, one can investigate the effect of wind shear combined with wide range of turbulence intensity by using BEM theory to predict the aerodynamic coefficients along the blade length.

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Figures

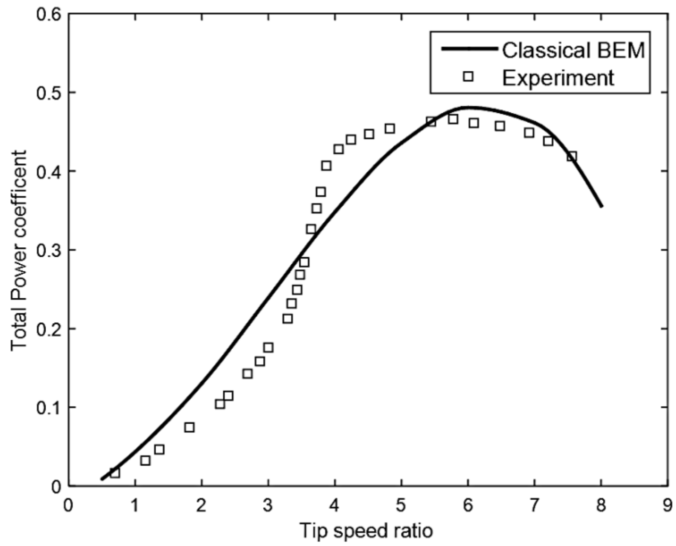


Figure 1: Validation of classical BEM results with experimental results obtained from Lee et al., 2016

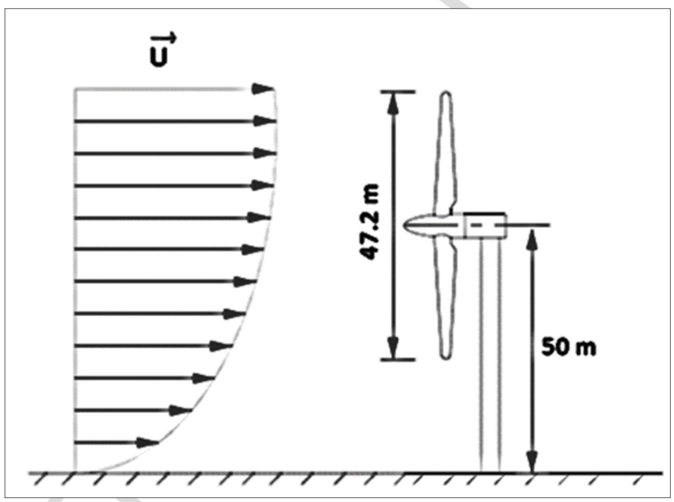


Figure 2: Schematic view of designed wind turbine

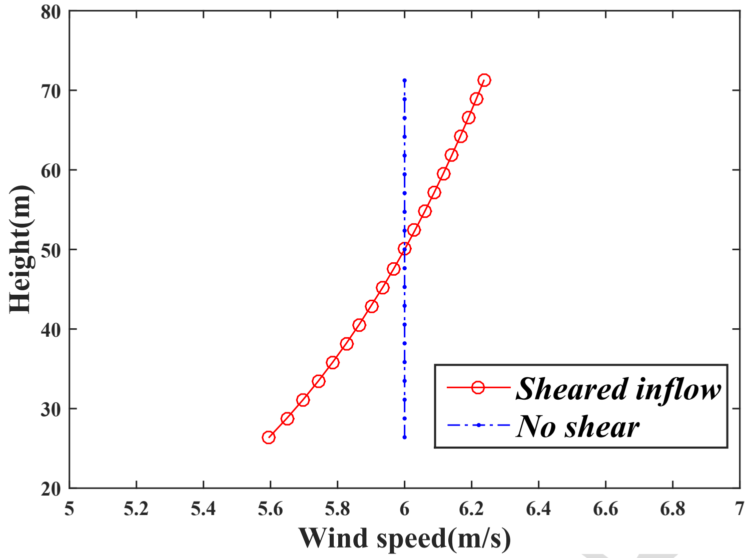
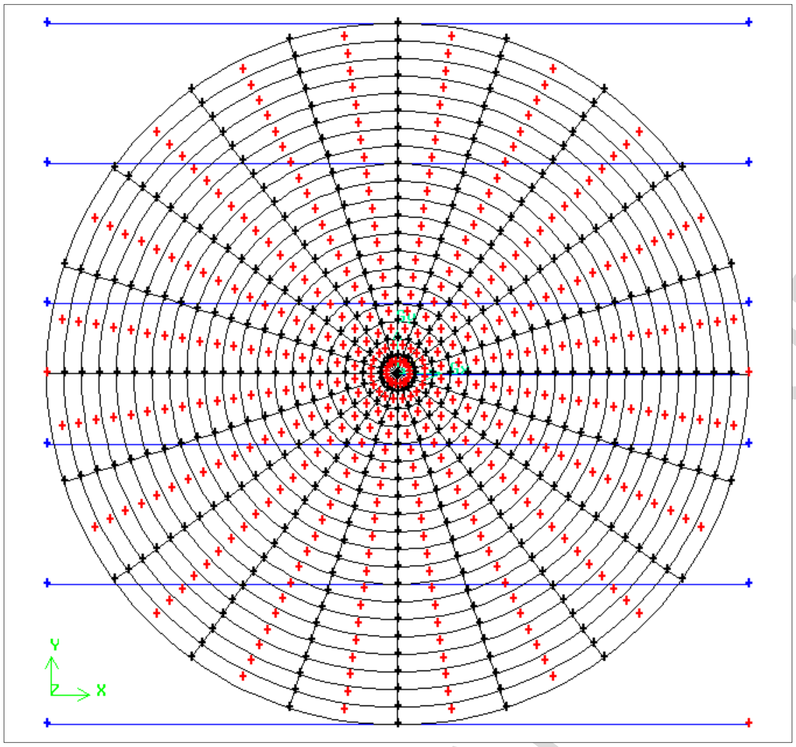
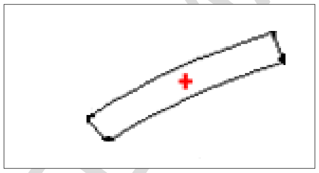


Figure 3: Wind speed in the case of sheared inflow and no shear



(a)



(b)

Figure 4: (a) Sectors on rotor swept area, (b) a sector on the rotor area

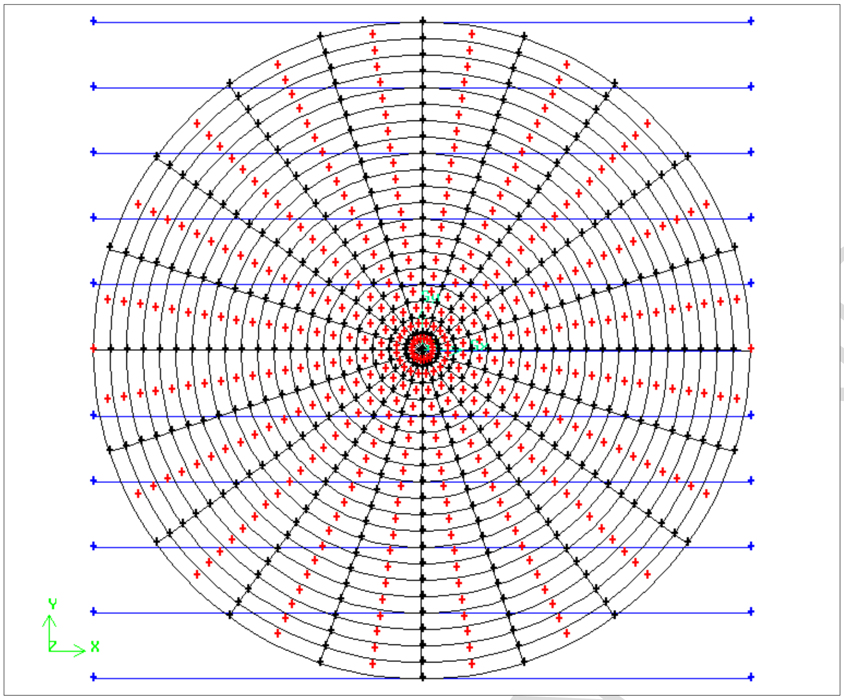


Figure 5: Sectors at rotor surface, using 10 slices along height

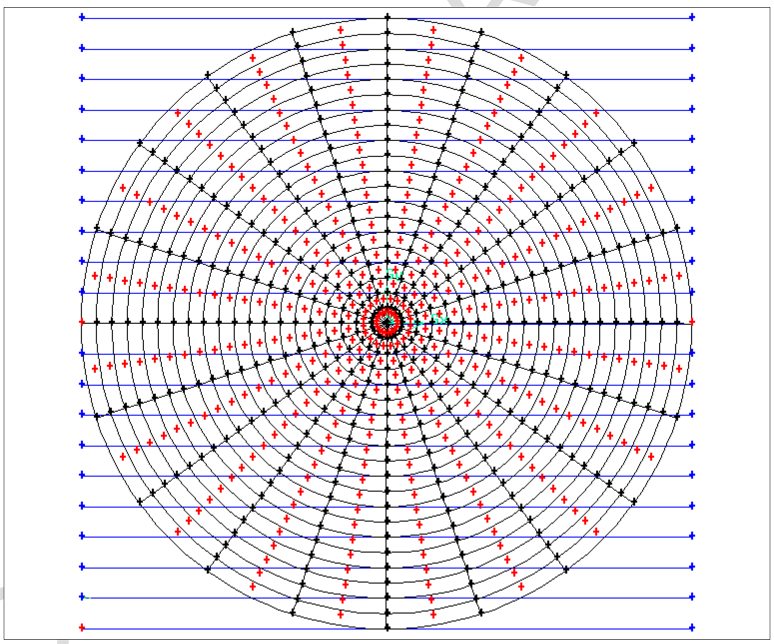
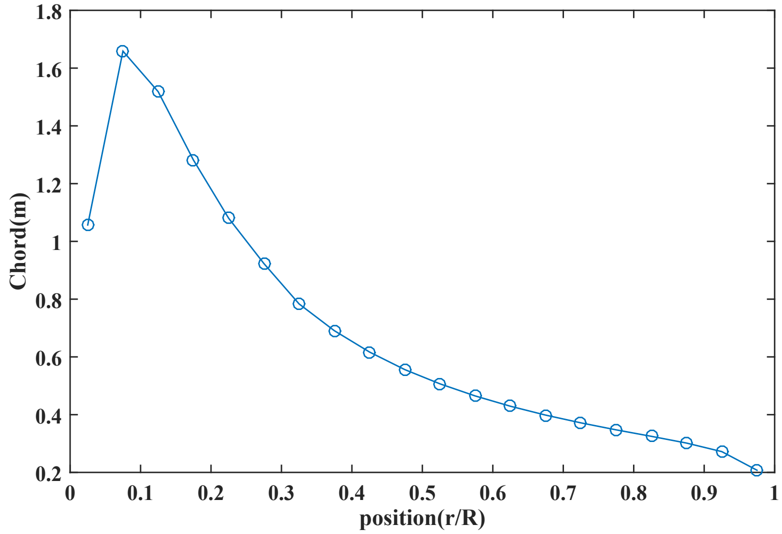
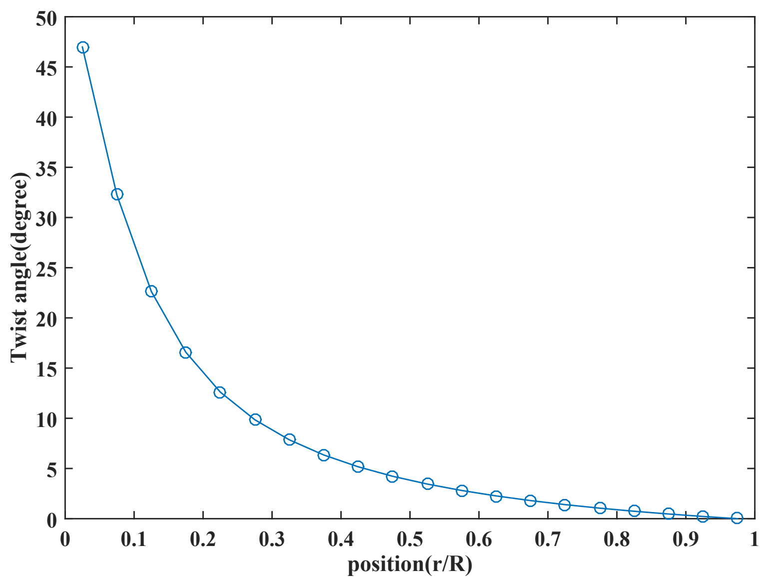


Figure 6: Sectors at rotor surface, using 20 slices along height



(a)



(b)

Figure 7: Chord and twist distributions along the blade length

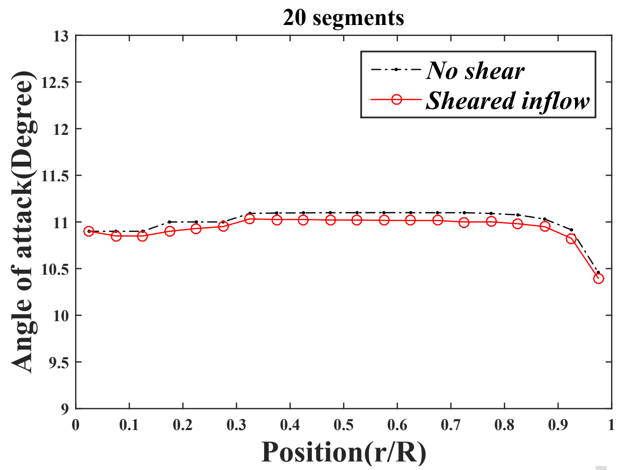


Figure 8: Distribution of angle of attack

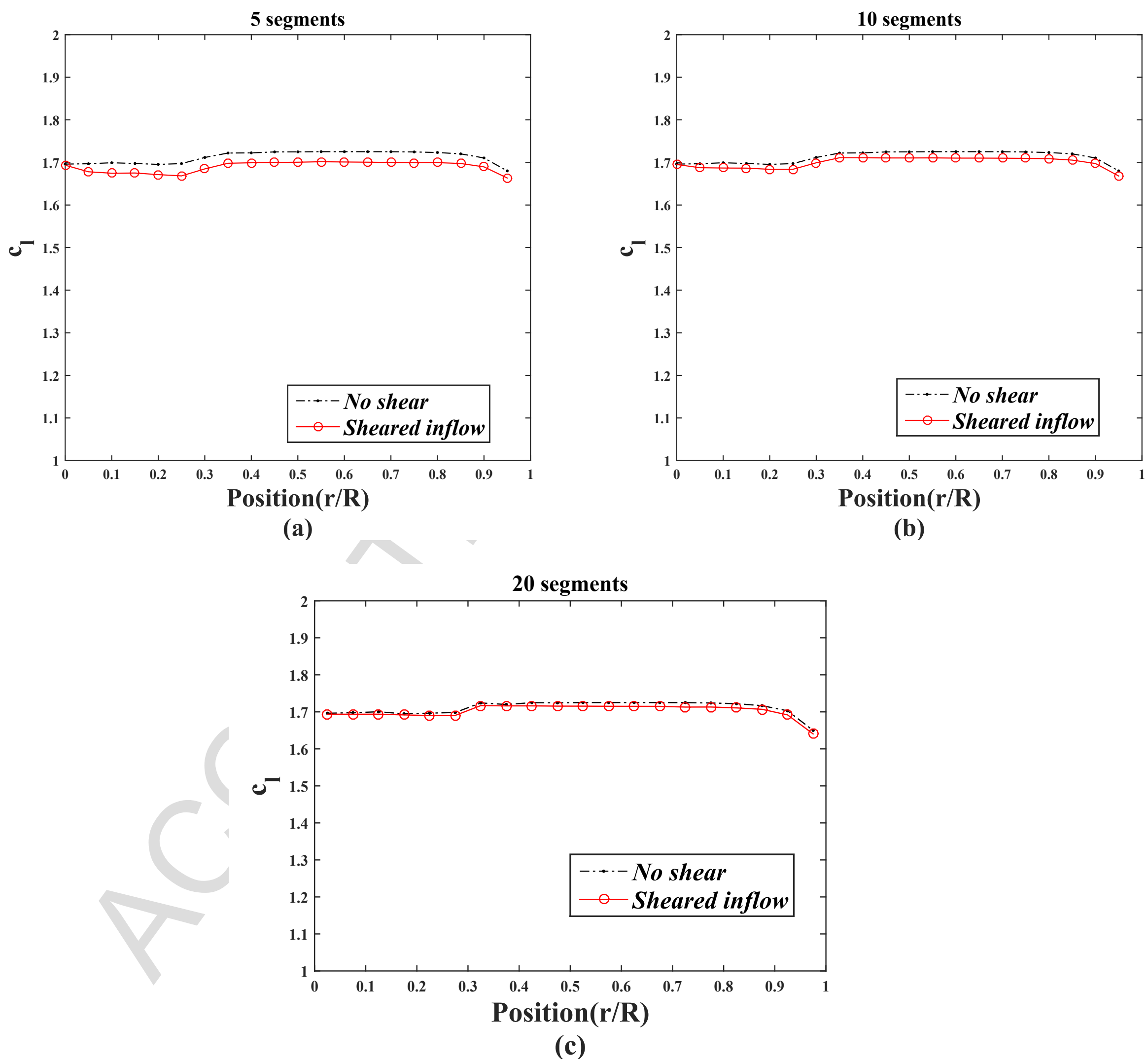


Figure 9: Distribution of lift coefficient

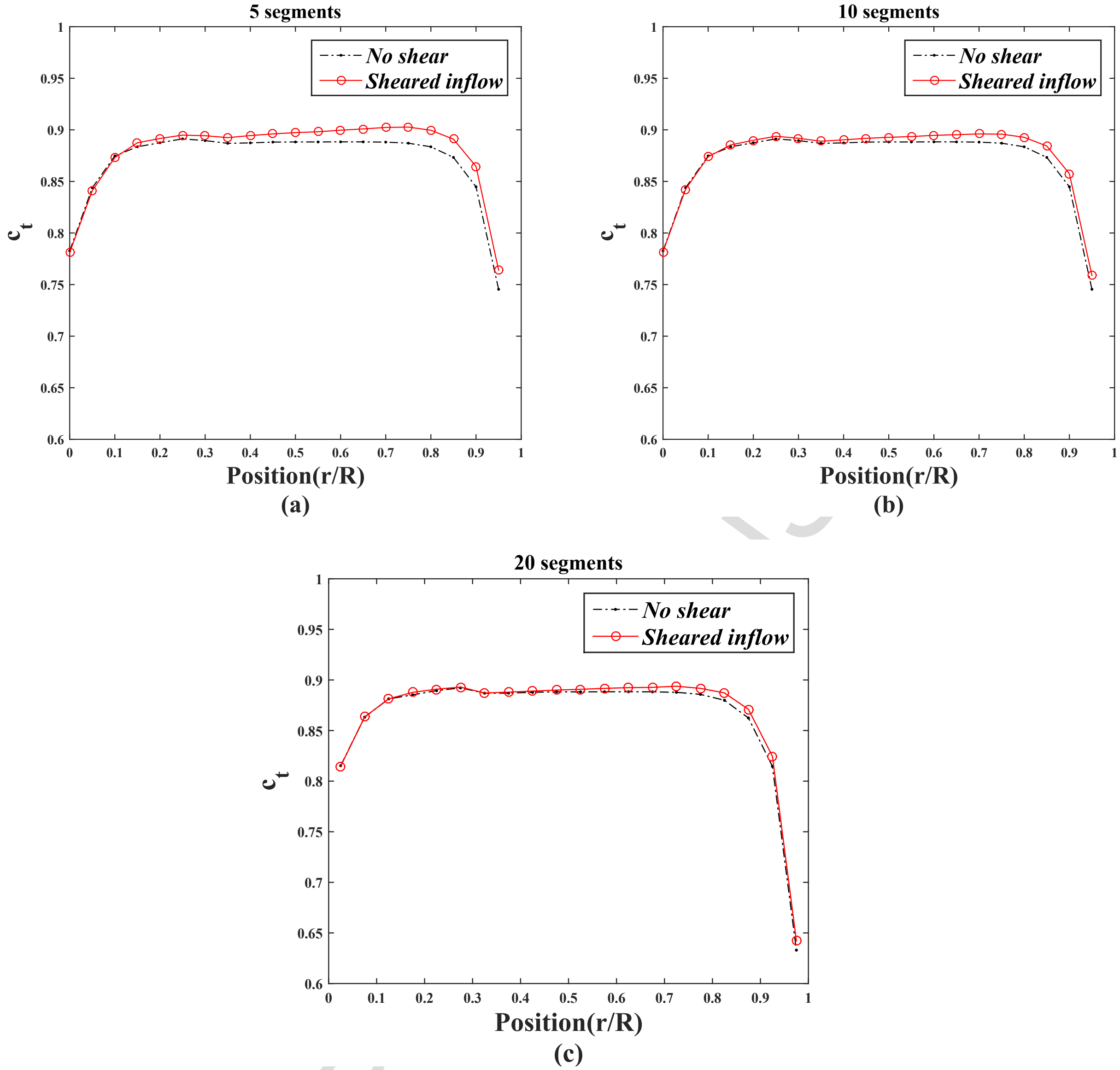


Figure 10: Distribution of thrust coefficient

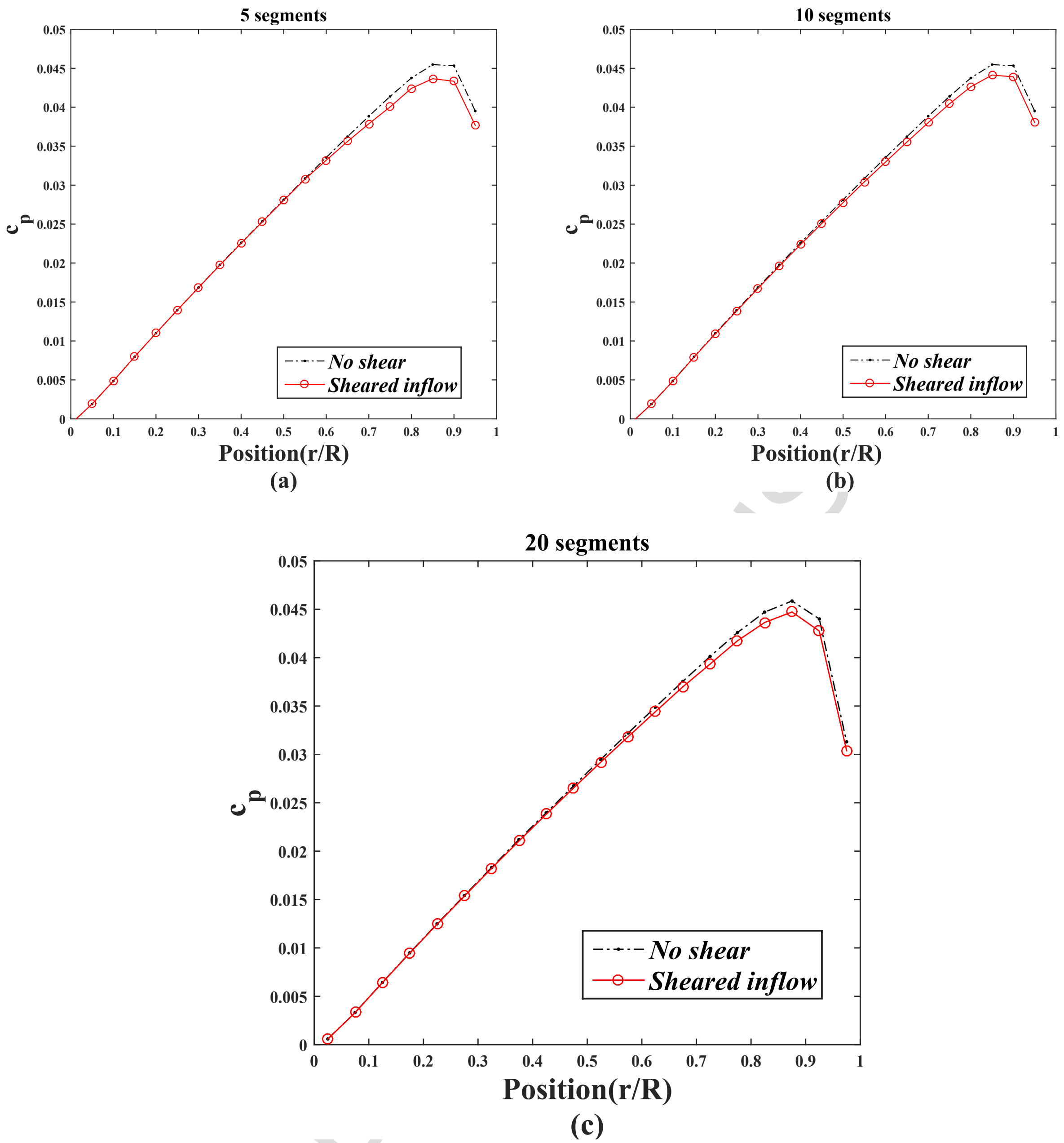


Figure 11: Distribution of power coefficient

Tables

Table 1: wind velocity at different height

Moalleman city	Height (m)	Velocity (m/s)
1	0	0
2	10	4.9
3	30	5.8
4	40	6.4

Table 2: Calculated velocity at different heights - 5 slices along the rotor height

Slice number	1	2	3	4	5
Velocity (m/s)	5.59	5.78	5.93	6.06	6.16

Table 3: Calculated velocity at different heights - 10 slices along the rotor height

Slice number	1	2	3	4	5	6	7	8	9	10
Velocity (m/s)	5.59	5.62	5.78	5.86	5.93	6	6.06	6.11	6.16	6.21

Table 4: Calculated velocity at different heights - 20 slices along the rotor height

Slice number	1	2	3	4	5	6	7	8	9	10
Velocity (m/s)	5.59	5.61	5.69	5.74	5.78	5.82	5.86	5.9	5.93	5.96
Slice number	11	12	13	14	15	16	17	18	19	20
Velocity (m/s)	6	6.03	6.06	6.09	6.11	6.14	6.16	6.19	6.21	6.24

Research highlights

- Uniform and non-uniform wind speed profiles are considered for design of HAWT.
- Power law is used to approximate the wind velocity profile as function of height.
- For more accurate evaluation, BEM theory is combined with wind shear effect.
- In order to consider wind shear effect, rotor swept area is divided into sectors.
- Aerodynamic properties are compared in presence and absence of wind shear effect.